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H^- ION SOURCE RESEARCH AT LOS ALAMOS*

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Abstract

Up to 160 mA of H^- ions has been extracted at 20 kV from a 10 by 0.5-mm^2 slit in a Penning surface-plasma source. Typically, 70% of the beam can be transported through a bending magnet to a Faraday cup or emittance scanner. Up to 90% transmission has been observed for some neutralizing gases. Average and pulsed cesium flows from the source were measured with a surface-ionization gauge. Operating parameters of the source and measurements of the emittance are reported.

Introduction

Many medium- and high-energy accelerators, including those at Argonne,[1] LAMPF,[2] TRIUMF,[3] and Fermilab[4], use H^- ions in lieu of or in addition to H^+ ions, for a variety of reasons. Accelerators producing beams with high average power (800 kW for LAMPF) require the lowest possible emittance to minimize beam losses and subsequent accelerator activation. The Penning surface-plasma source (SPS)[5] has low emittance and pulsed current suitable for use with these machines. Future accelerator applications may require intense dc sources of H^- ions.

Operation of the Penning SPS

The Los Alamos Scientific Laboratory (LASL) Penning source, adapted from the design by Dudnikov[5] for use with the USSR meson factory, is shown in Fig. 1. Electrons, confined by an ~0.2-T magnetic field oscillate between molybdenum cathodes, and ionize hydrogen gas at a nominal density of $4 \times 10^{15}/cm^3$. The ions drift to the cathodes, are accelerated through the plasma sheath, and impact on the cathodes, releasing secondary electrons and H^- ions. Only a low discharge current of 50-100 mA is produced at 650 V until cesium is added, usually from heating of a 2:1 mixture of titanium and Cs_2CrO_4 powders packed into the anode. When the cathode and anode temperatures are 400-500°C and the source housing is at 200°C, sufficient cesium is generated so that the discharge potential drops to 40-60 V for a 1-A dc current. Within the limitations of an ~50-W discharge power the uncooled source can be operated at any duty factor; for our purposes this is usually 7.5-Hz, 1-ms pulses of 100 A.

The cesium is believed to play two important roles:

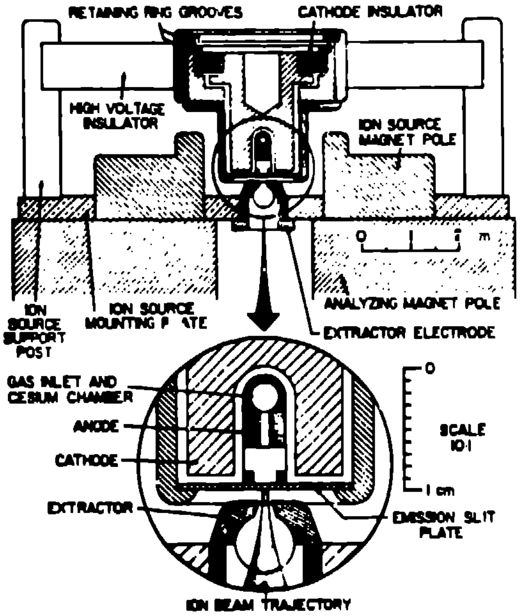

Fig. 1. Cross-sectional drawing of LASL Penning surface-plasma source.

1. It increases the secondary electron emission coefficient[6] $\gamma = j_e/j_+$ from about 0.1 for a pure molybdenum surface[7] to about 5.5.
2. It increases the secondary H^- ion emission coefficient[6] $K = j_-/j_+$ from a low value to about 0.7, where j_e, $j_{+,-}$ are the electron, positive ion, and negative ion current densities at the cathode, respectively.

The large value of γ presumably accounts for the low discharge voltage, which is strongly dependent on cesium coverage of the cathodes.

Our discharge will not operate below a minimum magnetic field B_m. Because positive ions must reach the cathodes to sustain the discharge, we expect that B_m must be large enough that the Larmor radius of the ions is less than the half-width w/2 of the anode chamber. The value of B_m for 100-A discharges in H_2 and in D_2 for two chamber widths is consistent with H^+ and D^+ ion energies kT of about 2 eV (Table I), where $kT = (eB_m\, w/2)^2/2M$. Derevyankin[8] operates a similar source with a field as low as 0.05 T, more nearly consistent with confinement of primary electrons whose momentum transverse and parallel to the field are comparable. Discharge noise disappears at about our value of B_m for both sources, a desirable condition for the production of low-emittance beams.

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Table I. Minimum Magnetic Field B_m Needed to Sustain Pulsed Discharge

Gas	w(mm)	B_m(T)	kT(eV)
H_2	2	0.21	2.1
H_2	3	0.15	2.4
D_2	3	0.20	2.2

A 100-A discharge in the 2 by 12-mm² discharge area will produce a 100-mA beam through the 10 by 0.5-mm² emission slit for a dc gas flow of 100-atm-cm³/min. The source volume is about 1 cm³, and the gas flow is pulsed with a Veeco PV-10 piezoelectric valve. A time of 1-2 ms is required to stabilize the source pressure, primarily because of mechanical oscillations in the valve. Source gas density, measured in the absence of a discharge, was $4 \times 10^{15}/cm^3$.

From the values of K and γ and the total measured cathode current density we calculated the electron, H^-, and positive ion current densities there. We estimate the plasma density by assuming that the ion current to the cathode j_+ consisted of protons with a temperature kT = 4 eV, so that $j_+ = \rho eV/4$ where $V = (8kT/\pi M)^{1/2}$. The measured, assumed, and calculated operating parameters of the source are summarized in Table II.

Cesium Flow Measurements

We measured[9] the cesium flow with a surface-ionization gauge (SIG) mounted on an insertable probe so that the distance between the SIG and the source emission slit could be varied.

Table II. Typical Source Operating Parameters

Measured	
Discharge voltage	40-120 V
Discharge current	100 A
H^- current extracted from 10 x 0.5-mm² emission slit	100 mA
Extraction gap	2.5 mm
Transport efficiency through 90° magnet	70%
Gas flow	100 atm cm³/min
Magnetic field in discharge region	0.21 T
Extraction power supply current	200 mA
Duty factor	7.5 Hz, 1 ms
Normalized emittance of 40% of the beam (63% for each plane)	0.04 x 0.03 (π cm·mrad)²
Current density at cathodes	208 A/cm²
H_2 density with discharge off	$4 \times 10^{15}/cm^3$
Assumed	
$kT_e = kT_+ = 4$ eV	
K = 0.7	
γ = 3.5	
Calculated	
Ion current density at cathodes	79 A/cm²
H^- current density at cathodes	21 A/cm²
Electron current density at cathodes	158 A/cm²
Plasma density	$3 \times 10^{14}/cm^3$

Charged particles were kept from the SIG by a combination of the magnetic field and a biased electrode at the SIG entrance. The cesium atoms entered the SIG and impinged on a tungsten filament at a temperature of 1500 K, hot enough to ensure that they would be re-emitted within 10 μs as Cs^+ ions.[10] The filament bias of +60 V with respect to the collector was sufficient to collect all Cs^+ ions but low enough to avoid excessive secondary emission at the collector. Hydrogen neutrals had little or no effect on the SIG. The cesium evolution rates from 2:1 mixtures of titanium with $Cs_2Cr_2O_7$ and with Cs_2CrO_4 powders were measured and the rates doubled for temperature changes of 20° and 32° respectively at 450°C, but the rate from the latter mixture was about four times that of the former. Source operation is essentially identical whether these mixtures or cesium metal-vapor ovens are used.

Absolute cesium flow rates from the source were calculated by using the solid angle subtended by the SIG and by assuming a modified isotropic angular distribution of cesium atoms from the source. When the source is operated with a 1-A dc discharge, the cesium flow for optimum H^- current is 0.5 mg/hr. The variations of discharge voltage and H^- ion current with the equivalent cesium density are shown in Fig. 2, where this density is that which would produce the observed flow rate in the absence of a discharge and hydrogen flow. When the discharge is abruptly extinguished, the cesium flow jumps about a factor of three, showing that even at a low discharge-current density of 4 A/cm², cesium flow is retarded by ionization.

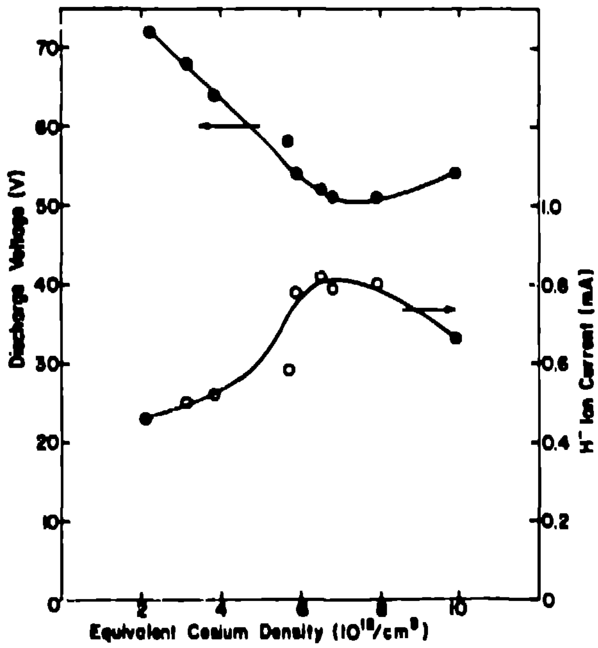

Fig.2. Variations of the discharge voltage and extracted H^--current vs equivalent cesium density for a 1-A dc discharge.

Flow during pulsed operation is more complex. For a 60-V, 100-A discharge, the cathode power density F is 8.3 kW/cm^2, assuming that 1/3 of the power goes to each cathode and to the anode.[6] The temperature rise of a semi-infinite solid subjected to this surface heating would be[11] $\Delta T = 2F(t/\pi K\rho C)^{1/2} = 140°C$ at $t = 1$ ms, where $K = 1.38$ W/cm°C, $\rho = 10.2$ g/cm^3, and $C = 0.3$ J/g°C for molybdenum.

For an average cathode temperature of 500°C and a fractional equilibrium coverage $\theta = 0.65$, the evaporation rate of the cesium will be increased by a factor of ~100 for this temperature rise, which would lead to a new equilibrium value of $\theta = 0.45$; however, we believe that θ actually increases during the pulse because of discharge pumping. As the cesium flow from an independently controlled oven is increased up to the optimum value, the discharge voltage and noise decrease and the H$^-$ current increases. The same trends are observed as a function of time for a 1-ms pulse when the average cesium flow is low. When the discharge is extinguished, cesium rapidly evaporates from the cathodes. From the evaporation rates given by Taylor and Langmuir[10] for cesium on tungsten, we estimate that θ decreases by 0.05-monolayer in the first 20 µs with a rapid drop in evaporation rate thereafter. The atoms are quickly readsorbed on cooler surfaces of the source so that there is a short burst of cesium flowing from the source.

We calculate that the cesium flux N as a function of time t at the SIG, at a distance d from the source, using the equations of flow for an ideal oven[12] for a short time δt is

$$N = N_0\ (t_0/t)^5 \exp(5/2[1-(t_0/t)^2]) \tag{1}$$

where

$N_0 = Af\Omega n\delta tkT\ (5/e)^{5/2}/4\sqrt{2}\ \pi^{3/2}Md$

$t_0 = (Md^2/5kT)^{1/2}$

A = emission area of source

f = flux distribution factor[9]

Ω = solid angle subtended by SIG

n = density of cesium atoms in source

This calculated flux is compared with the measured data in Fig. 3, for which N_0 and t_0 have been adjusted to fit the data. A cathode temperature T of 730°C, near the value estimated at the end of the pulse, is calculated from the value of t_0. Scattering of the cesium atoms by the H_2 gas was not taken into account, but this would improve the fit for long times of flight. As first noted by Belchenko[13] the cesium consumption for a dc source might be much less than the typical 1 mg/hr used for pulsed operation.

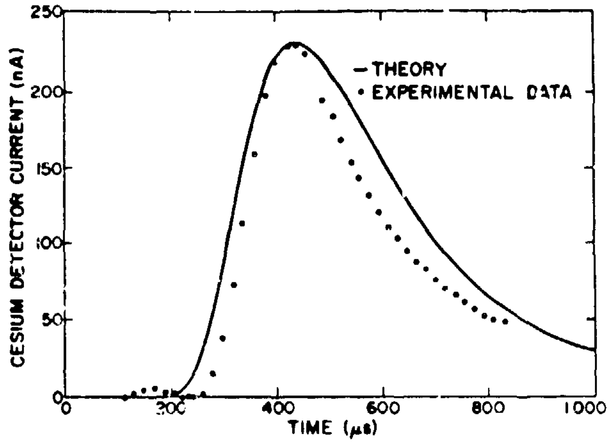

Fig. 3. Flow of cesium from source vs time after 100-A discharge is extinguished. The is a fit of Eq. 1, assuming a cathode temperature T of 730°C.

H- Plasma Losses

From the plasma densities given in Table II we can estimate the attenuation for an H$^-$ ion traveling a distance ℓ from the cathode to the emission slit. The factor a_e for attenuation by electron collisions is $a_e = \exp(-\rho_e\langle\sigma_e v_e\rangle\ \ell/v_-) = 0.2$ for $\ell = 3$ mm, 60-eV H$^-$ ions, and an electron temperature of 4 eV, for which, $\langle\sigma_e\ v_e\rangle = 2 \times 10^{-7}$ cm^3/s (Ref. 14). The factor a_+ for proton collisions is 0.2, whereas that for H_2 collisions is 0.6. The attenuation by collisions with slow H^0 atoms leads mostly to slow H$^-$ ions. Because ρ_0 is not known, we can only state that if it is 8×10^{14}/cm^3 (10% of the H_2 dissociated) then $a_0 = 0.2$. As H$^-$ ions are thermalized, a_e becomes the dominant factor. It seems clear that only a small fraction of cathode-produced H$^-$ ions would reach extraction. From Table II the H$^-$ current density from each cathode is 21 A/cm^2, whereas the extracted current density is only 2 A/cm^2; therefore, if the H$^-$ ions are produced at the cathode, the current density is attenuated by a factor of ~20 before extraction.

To get some measure of this effect, we varied the anode web thickness and measured the H$^-$ current under otherwise identical conditions. This web (Fig. 4) serves to partially filter plasma electrons from the emission area and is normally 1-mm wide. The H$^-$ current was found to be attenuated by e^{-1} in a distance of about 1.4 mm. If H$^-$ ions from the cathode had a similar attenuation the factor would be 8, over the 3-mm distance. The agreement with the above estimates is rough, but it seems clear that H$^-$ ions are subject to severe losses before extraction. Although the H$^-$ production efficiency increases for small web thickness, the electron loading of the

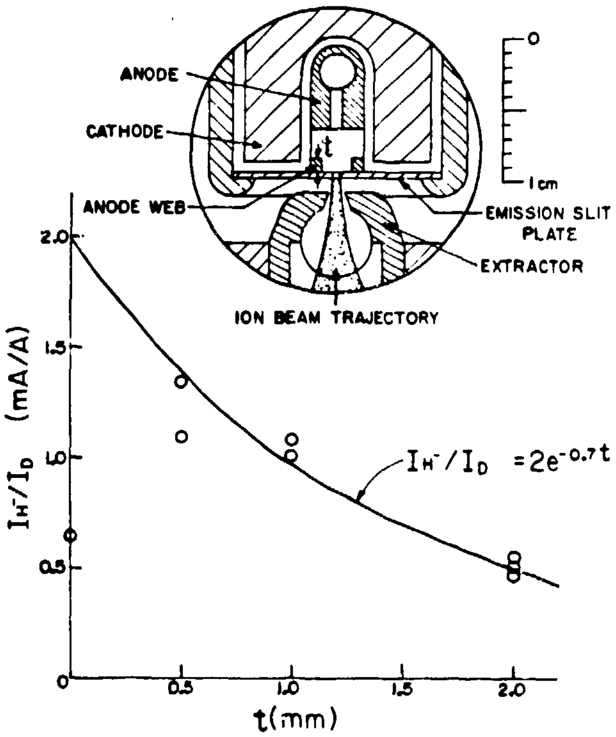

Fig. 4. H^- production efficiency (I_{H^-}/I_D) vs anode web thickness t. A curve with exponential dependence on t has been fit to the data.

extraction power supply increases from 100% of the H^- ion beam to about 300% for a web thickness change of from 1 mm to 0.5 mm, and for zero web thickness it becomes difficult to operate the extractor.

Extraction and Transport

Extraction is difficult if the extraction gap g is small enough to allow electrons to cross. In the presence of a magnetic field B, and extraction voltage ϕ, electrons cross the gap unless $g = (2m\phi/e)^{1/2}/B = 2.3$ mm for $B = 0.21$ T, $\phi = 20$ kV. The extractor is made of molybdenum so that occasional overheating does not melt it. It is desirable to operate the extractor at a warm temperature to evaporate impinging cesium. A cooled extractor was unsuccessful because of cesium condensation.

The beam diverges strongly at the entrance to the 90°, n = 0.85, 8-cm-radius magnet but is reasonably well focused at the exit. Up to 160 mA has been extracted at 20 kV into the Faraday cup, 2 cm past the extractor[I(0°)], a current density of 3.2 A/cm^2 at extraction. Extraction from circular emitters has also been successful.[15] Table III lists parameters for extracted and transported beam for several different emission geometries, where I_D = discharge current, I(90°) is the H^- current transported to a Faraday cup, 6 cm past the 90° magnet, and j_{em} is the H^- emission current density.

Increasing the hydrogen feed rate beyond the minimum for stable discharge operation causes the H^- beam to be attenuated in a manner consistent with the cross sections for collisional detachment, both in the source and in the 90° magnet. If the gas is pulsed instead of flowed continuously the required flow of cesium is reduced. The transport efficiency through the 90° magnet improves, however, when some other gases are added to the vacuum system. Ion-optics calculations using the Kapchinskij-Vladimirskij equations[16] for beams with space charge and emittance show that an unneutralized beam of 100 mA at 20 kV would diverge in the magnet and be poorly transmitted, whereas 70% transmission is typically observed; implying at least partial neutralization. A neutralization monitor consisting of a biased collector plate shielded by a grounded screen was installed at the magnet exit with the 4 by 2-cm^2 collector plate parallel to the magnet poles so that slow electrons and ions would be collected. The energy spectrum of charged particles was measured by varying the bias voltage of the collector.

For low-energy H^- ion beams, the probability of ionizing the residual gas is much less than that for producing slow electrons by H^- stripping. The ionization cross sections for H^- and H^+ ions beam have been[17] found to be the same. The ratio R_c of electrons to ions produced in various gases at 20 keV was calculated from existing data[7,17,18] and is given in Table IV. Our measured value R_m is in rough agreement.

The electron energy distribution was approximately Maxwellian with a temperature of about 25 eV, twice that for electrons produced by proton ionization of gases.[19] Because the stripped electrons have kinetic energy (11 eV for 20 keV H^- ions) a higher temperature might be expected. Generally gases heavier than helium improved the H^- transmission by about 15%, resulting in up to 90% transmission. The optimum density in the transport region was about 10^{12}/cm^3 for all gases.

Table III. Extracted and Transported Beam

Emitter (mm)	Extractor (mm)	Gap (mm)	I_D (A)	I(0°) (mA)	I(90°) (mA)	j_{em} (A/cm2)	ϕ (kV)
10x0.5	20x1	2.5	108	100	80	2	18
10x0.5	20x1	2.5	150	160	110	3.2	20
1 diam	1 diam	1.2	100	33	-	4.1	15
2 diam	2 diam	2	100	57	-	1.8	20

Table IV. Beam Transport with Neutralizing Gas Added

Gas	R_c	R_m	kT_e (eV)	Transmission Improvement over that for H_2
H_2	7.8	5	24	0%
N_2	5.1	-	-	19%
Ne	8.5	10.4	28	-
Kr	7.2	9	25	17%

Transmission efficiency is strongly dependent on beam-current noise. In a single pulse, the H^- current I(0°) may rise 30% during a transition from a noisy to a quiet discharge, and I(90°) may rise by 100% or more.[20] Probably the neutralizing plasma cannot track the fluctuating current, which, along with a fluctuating location of the plasma surface at the source, would lead to a time-averaged emittance increase. Measurements have shown that there can be a factor of 3 variation in emittance under these conditions.[15]

The 90° magnet used results in a circular beam at the exit with about 100 times lower density than at extraction, desirable for many subsequent accelerator applications. The magnet also induces substantial coupling between the x- and y-planes (the 1- and 0.05-cm directions along the emission slit respectively). There are two dominant aberrations[21] in this case, $\delta y' = A_1 x' y$ and $\delta y' = A_2 xy$. These arise from a combination of the sextupole components of the bending and of the exit fringe fields, the latter being essentially fixed but the former being adjustable by magnet pole design. The minimum net aberration is achieved by taking a finite value of the bending sextupole to partially cancel the effects of the exit fringe fields. If the beam size (about 2-cm diam) were smaller in the magnet, perhaps by means of better extraction optics and a quiet discharge, the aberration would be reduced. Even so the emittance is acceptably low.

Emittance

The emittance of an ion beam has as its origins

1. the temperature of the ions in the plasma and the size of the emitter,
2. ion-optical aberrations in the extraction and transport elements,
3. nonlinear space-charge forces, and
4. time-dependent fluctuations in the current, leading to time-averaged increase in emittance.

In a typical emittance scanner[20] phase space is mapped as a function of threshold t, where

$$t = (\partial^2 i/\partial x \partial \dot{x})/(\partial^2 i/\partial x \partial \dot{x})_{max}$$

averaged over y, $\dot{y}$ space. Then the fraction F of current within a normalized emittance ϵ is given by

$$F(t_0) = \iint_{t_0 \le t \le 1} (\partial^2 i/\partial x \partial \dot{x})\,dx\,d\dot{x} \Big/ \iint_{0 \le t \le 1} (\partial^2 i/\partial x \partial \dot{x})\,dx\,d\dot{x}$$

and

$$\epsilon(t_0) = \iint_{t_0 \le t \le 1} dx\,d\dot{x}/c$$

As a simple model we assume that the ions at the plasma surface have uniform spatial density and a temperature T, and we neglect other sources of emittance (2,3,4 above). Then by Liouville's theorem[22] F and ϵ are invariant in transport, even in the presence of linear space-charge forces, so that the calculated dependence of F on ϵ at the plasma surface may be compared directly with that at the emittance scanner plane.

For a slit emitter, t is independent of x over the slit of width 2R, so that $t = \exp(-m\dot{x}^2/2kT)$ $|x| \le R$. Evaluation of the integrals leads to

$$F = \mathrm{erf}(\pi\epsilon/4R[2kT/mc^2]^{1/2}) \quad (2)$$

The normalized rms emittance is defined by[22] $\epsilon_{rms} = 4\sqrt{\langle x^2\rangle\langle \dot{x}^2\rangle - \langle x\dot{x}\rangle^2}/c$ so that for the slit $\langle x^2\rangle = R^2/3$, $\langle \dot{x}^2\rangle = kT/m$, $\epsilon_{rms} = 4R(kT/3mc^2)^{1/2}$ and $F = \mathrm{erf}(\pi\epsilon/6^{1/2}\epsilon_{rms})$. For a circular aperture t is no longer independent of x but is given by $t = (1-x^2/R^2)^{1/2} \exp(-m\dot{x}^2/2kT)$. Now F is not a simple function of ϵ, but the integrals were evaluated numerically, and the results are very close to those for the slit. It is still possible to evaluate ϵ_{rms} analytically, and the results are[22] $\epsilon_{rms} = 2R\,(kT/mc^2)^{1/2}$. According to this model the rms emittance contains 93% and 91% of the beam for the slit and the circular aperture emitters, respectively.

The emittance of a 17-keV, 80-mA beam extracted from a slit was measured with a scanner having a pair of movable slits, between which are beam-deflecting plates so that the current distribution can be measured as a function of angle. The calculated fraction of the total current within a given normalized emittance is shown in Fig. 5, along with a fit of Eq. 2, using T as the adjustable parameter.

We believe that fast H^- ions from the cathodes make resonant charge-exchange collisions with H atoms in the discharge; therefore their temperature should be that of the H atoms. The latter temperature is not known, but the Franck-Condon energy for collisional dissociation[23] of H_2 is > 2 eV/atom. The temperature deduced from the fit for the x-plane (2R = 10 mm) is 5 ev, in the expected range. For the y-plane (2R = 0.5 mm) the deduced temperature is 820 eV; however, we know[21] that the bending magnet couples the x- and y-plane emittances so that the larger emittance of the x-plane masks that of the y-plane. The large effective ion temperature reflects the small initial plasma radius for the y-plane. The fit of the theory to the data shows that the velocity distributions are not exactly

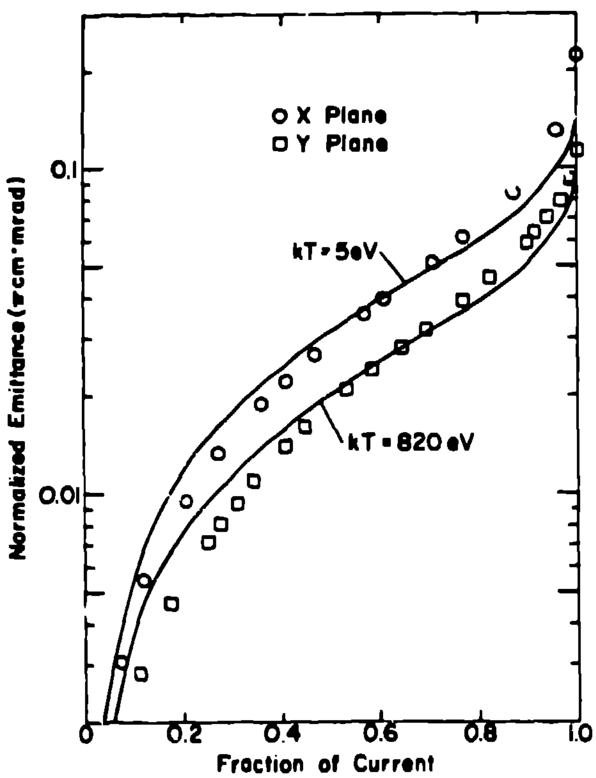

Fig. 5. Normalized emittance vs fraction of an 80-mA beam extracted from a 10 x 0.5-mm² slit. The curves are fits of Eq. 2 assuming kT = 5 ev and 80 ev in the x- and y-planes, respectively.

Maxwellian, and this is typical of all of our emittance measurements for beams extracted from slit emitters. Better fits have been observed for circular aperture emitters.[15]

Future Plans

The SPS principle using Penning geometry has been extended to a design with rotating electrodes to help dissipate the high power density required to produce 100 mA of H⁻ ion current dc. This concept is now being tested.[2,4] A 250-kV H⁻ injector is being built to provide beams for accelerator structure tests. This injector is designed to produce 100-mA beams with a pulse length of 1-ms and a frequency of 7.5 Hz.

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